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ANOMALY PATTERNS OF CLIMATE OVER THE WESTERN UNITED STATES, 1700–1930, DERIVED FROM PRINCIPAL COMPONENT ANALYSIS OF TREE-RING DATA

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ABSTRACT

Major anomaly patterns of annual tree-ring growth in "drought-sensitive" trees of the Western United States, 1931–1962, seem to reflect corresponding patterns in monthly precipitation amounts, which in turn may be related to circulation anomalies. The three most important anomaly patterns that dominated the 1931–1962 period were also prominent in the tree-growth data during the preceding period 1700–1930. These patterns can thus be expected to maintain their importance during at least the immediate future. Time series of eigenvector amplitudes show how the relative importance of the anomaly patterns changes through time. These can be studied for properties lending possible forecasting value and may provide important insight into the past behavior of the atmospheric circulation over the Western United States.

1. INTRODUCTION

In a recent article, Sellers (1968*b*) applied principal component (eigenvector) analysis to monthly precipitation data for the period 1931–1966 to delineate characteristic precipitation anomaly patterns in the Western United States. The results show that about half the total variance in precipitation in each month can be explained by a combination of only three patterns and that the same dominant patterns could be recognized in most months. However, Sellers points out that the forecasting value of the eigenvectors might be limited because of the apparent absence of systematic variations through time and because we have no assurance that the same patterns will continue to dominate in the future.

There are striking similarities between the characteristic anomaly patterns of precipitation and tree growth in the Western United States. This paper illustrates these similarities and suggests ways to use tree-ring data in studies of precipitation and circulation anomaly patterns.

The theory underlying principal component analysis and the computations involved, based on a correlation matrix, have been reviewed by Sellers (1968*b*) and will not be repeated here. When applied to time series from a spatial array of m data points, the analysis results in a set on m eigenvectors. Each eigenvector, F_k, can be plotted and contoured to display the spatial variation exhibited by the component. The resulting mapped pattern has been termed a "characteristic anomaly pattern" (Grimmer 1963). A limited number of such patterns may explain most of the variance in the original data field. Furthermore, the dominant patterns can also have clear-cut physical explanations.

The amplitude of an eigenvector of a spatial array provides a measure of the change in relative importance of the associated anomaly pattern with time. The amplitude (q) of eigenvector F_k in year i is calculated as the sum of the products of its components f_j and the normalized departure of the quantity, p, being measured at data point j in year i. That is,

$$q_{ik}=\sum_{j=1}^{m} f_{jk}p_{ij}.$$

Thus, the amplitude of an eigenvector will be large when the observed anomaly pattern coincides with the characteristic anomaly pattern for that eigenvector, provided the observed departures are also large. If the amplitude is large in absolute value, but negative in sign, the observed departure resembles the characteristic pattern, but is opposite in sign.

The importance of a particular anomaly pattern in a different time period can be determined by first calculating the estimate $\hat{p}$ for the spatial array of data points according to the relationship

$$\hat{p}_{ij}=f_{jk}\,q_{ik}.$$

The percent of total variance in the independent data set "explained" by the eigenvector is equal to the square of the correlation coefficient between the estimated ($\hat{p}$) and observed (p) values.

There are some differences in the nature of the basic data that affect the outcome of the analyses that are compared in this paper. First, Sellers used spatially averaged precipitation data from each of 50 climatological divisions. Because such averaging enhances point-to-point correlations, it results in smoother spatial variation in the components of each eigenvector than would have been obtained if individual station records had been used. The tree-ring chronologies were each compiled from the growth records of conifers from an area that is small in comparison with the average climatological division. The tree-growth anomaly patterns would

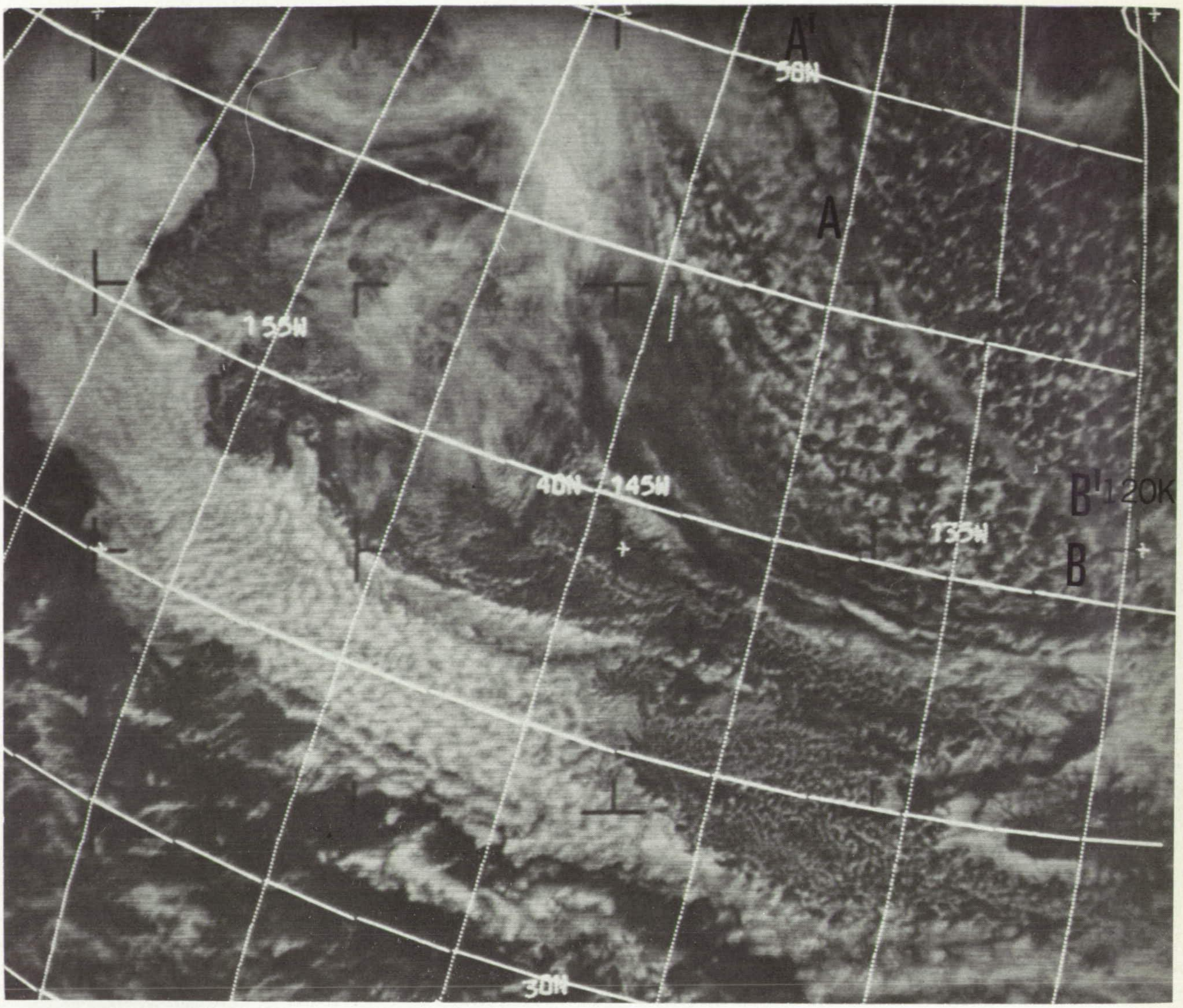

FIGURE 2.—ESSA 9 view, pass 5291, at 2330 GMT on Apr. 25, 1970.

The large area of mountain wave clouds, at C, over the Western United States is further evidence of this belt of strong winds.

The cyclonically curved portion of the jet stream, from the 0000 GMT NMC (National Meteorological Center, Suitland, Md.) 300-mb chart of Apr. 26, 1970, extends from A′ to B′ to C′ to D′ on figure 1 and from A′ to B′ on figure 2. Representative wind speeds from the 300-mb chart are also plotted on the photographs.

Figure 2, an ESSA 9 photograph taken approximately 2 hr later than figure 1, shows the cirrus associated with the jet stream extending from A to B. The rapid rate of dissipation of the cirrus during the 2-hr period is illustrated by comparing the large cirrus sheet on figure 1 with the remaining cirrus streak on figure 2.

In this case, the change from unstable cloudiness poleward of the jet to stable cloudiness equatorward of the jet is minimal, except at D where the change to stable cloudiness is more complete.

be expected to show correspondingly greater irregularity than Sellers' precipitation anomalies.

Second, and perhaps more important, is the fact that Sellers performed a separate analysis using precipitation amounts for each month of the year; whereas we have used annual tree-ring indices. These indices represent the growth response that is the integrated effect of both moisture and temperature upon physiological processes in these conifers for an 11- to 12-mo period before initiation of growth and for an additional 2 to 3 mo during the growing period (Fritts 1966). Because of these incompatabilities, the comparisons made in this paper are largely qualitative and feature only the more striking similarities between the two types of data. More rigorous comparisons are under investigation by the second author and will be reported elsewhere.

2. BASIC DATA AND PROCEDURE

A set of 49 chronologies of tree-ring indices from the Western United States was used in this study. Each chronology is a time series of mean ring-width indices from a replicated sample of trees from a small area (Fritts 1969). The locations of the sample areas are shown in maps 5–12 of figures 1 and 2. In part, the tree-growth data represent updated versions of an earlier set of 26 chronologies described by Fritts (1965). However, new chronologies have been added in areas of previously poor coverage and in regions such as the Northern Rocky Mountains where correlation falls off rapidly with distance. The chronologies are from several different coniferous species that undoubtedly differ somewhat in their growth response to climate (Fritts 1965, 1966). However, they are all "drought sensitive" tree-growth records and may be considered as annual "outputs" from a system that is affected by a set of weighted "inputs" representing the limiting effects of drought and temperature on plant processes during each month of the year (Fritts 1969). Differences among species may be represented as differences among the weights assigned to the monthly inputs.

All but two of the chronologies begin before 1600 A.D. However, only the indices for the period 1700–1962 were used in this work. For comparing the tree-growth eigenvectors with those obtained by Sellers for monthly precipitation, a principal component analysis was first made using indices for the subperiod 1931–1962. An independent analysis was then made for the subperiod 1700–1930. For providing a basis for comparison of the tree-growth eigenvectors for the two subperiods, the amplitudes were calculated (1) from the dependent data, which represent the same subperiod as that for which the eigenvectors were derived, and (2) from the independent data representing the other subperiod. Because differences in the mean and variance between the subperiods might affect the comparison, amplitudes were calculated from the independent data after normalization, using the mean and standard deviation for the dependent subperiod.

3. RESULTS

Over half of the total variance in tree growth during the period 1931–1962 can be explained by the four most important eigenvectors (table 1). Their characteristic anomaly patterns have been labeled A, B, C, and D in order of decreasing importance and are shown in figures 1 and 2 (maps 5, 6, 7, and 8, respectively). Pattern A is characterized by components with the same sign throughout the Western United States, with values reaching a maximum in the Southwest. Pattern B is composed of areas with opposite signs in the northwestern and southeastern parts of the region. Pattern C associates anomalies of opposite sign in the northeastern and western parts of the region, and pattern D consists of two areas, one in the northwest and one in the southeast, with the same sign, separated by a northeast-southwest-trending belt of opposite sign.

To illustrate the similarity of the tree-growth and precipitation anomaly patterns, we have reproduced certain of Sellers (1968*b*) maps in figures 1 and 2 (maps 1, 2, 3, and 4). Although we have selected these maps arbitrarily, they show the types of patterns described by Sellers as occurring most frequently in the monthly precipitation data for the 1931–1966 period. Since precipitation is known to be a major factor governing soil moisture, plant-water relationships, and the growth of the annual rings in trees on semiarid sites (Fritts 1965), the tree-growth anomaly patterns should reflect the types of precipitation anomalies that were dominant during the same period.

For testing the associations inferred from the similarities of anomaly patterns, the amplitudes of the first four tree-ring eigenvectors were correlated with the amplitude series for the four most important eigenvectors of monthly precipitation (Sellers 1968*a*). Correlation coefficients significant at the 95-percent confidence level were obtained for the correlation of the first tree-ring eigenvector (pattern A) with the first eigenvector of precipitation in October, January, March, April, and June and with the second precipitation eigenvector for December. Each of these precipitation anomaly patterns resembles tree-ring pattern A, although the area of maximum precipitation anomaly shows a systematic seasonal displacement, as pointed out by Sellers (1968*b*). However, when the same procedure was followed using the second, third, and fourth tree-ring eigenvectors, only a few significant correlations were found. Furthermore, the high correlations seemed unrelated to similarities in map patterns. Apparently, the less important eigenvectors of monthly precipitation cannot be individually related to annual tree-growth eigenvectors, despite the qualitative similarity of the associated anomaly patterns. Since the tree-growth patterns represent the average effect of climate throughout the entire year, more conclusive results would probably be obtained if annual or seasonal precipitation data were used to derive the eigenvectors. It would further improve

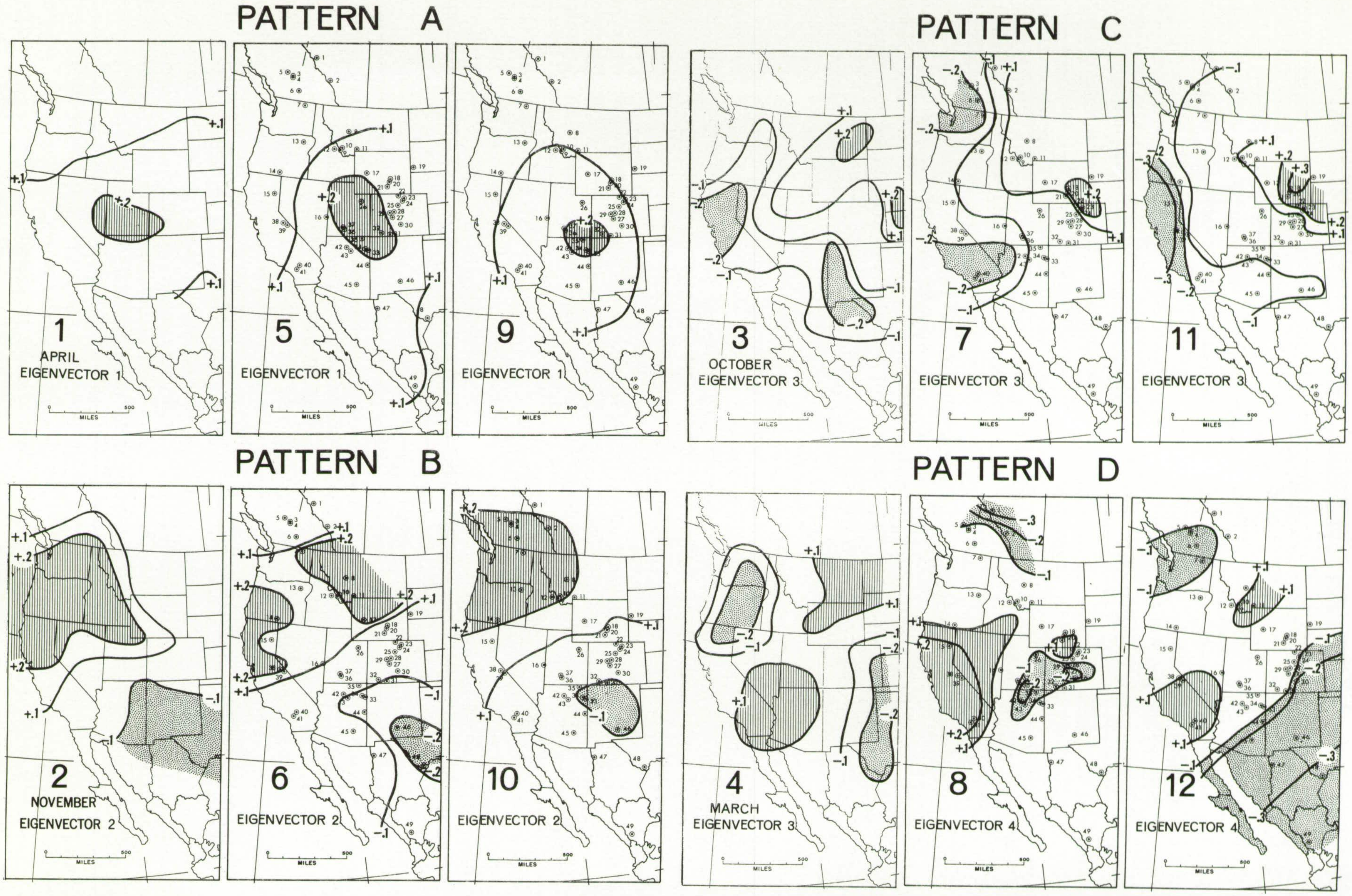

FIGURE 1.—Characteristic anomaly patterns of precipitation and tree growth; maps 1–4, precipitation anomalies adapted from Sellers (1968*b*); maps 5–8, tree-growth anomalies from 49 tree-ring chronologies 1931–1962; maps 9–12, tree-growth anomalies from the same 49 tree-ring chronologies 1700–1930. (See also table 2.)

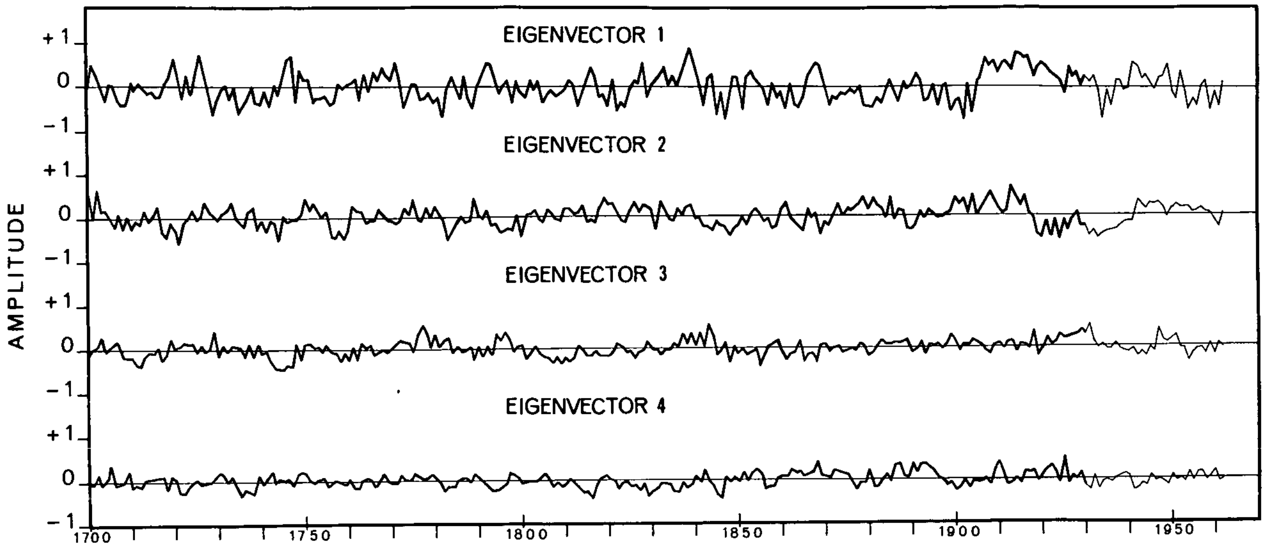

FIGURE 2.—Amplitudes of the first four eigenvectors of tree growth. The eigenvectors were calculated from data for 1700–1930; the heavy line indicates dependent data; the light line, independent data. (See also table 2.)

TABLE 1.—*Percentage of variance explained by most important eigenvectors of tree growth. Separate sets of eigenvectors were obtained for each subperiod (dependent data), but amplitudes were calculated for both the dependent and independent data sets*

Type of data	Period of analysis	Characteristic pattern				Total
		A	B	C	D	
Dependent	1931–1962	24.9	16.7	10.1	7.6	59.3
Independent	1700–1930	16.7	7.1	3.9	2.2	29.9
Dependent	1700–1930	22.5	11.3	6.5	5.0	45.3
Independent	1931–1962	17.0	11.7	5.1	2.5	36.3

TABLE 2.—*Percentage of variance explained by eigenvectors of precipitation during selected months (from Sellers 1968b); period of analysis, 1931–1966; italicized values correspond to eigenvectors mapped in figures 1 and 2*

Month	Characteristic pattern			
	A	B	C	D
April	*27.9*	20.2	9.4	-----------
November	24.6	*22.3*	11.5	-----------
October	30.2	17.7	*9.9*	-----------
March	31.2	14.8	-----------	*10.4*

the analysis to determine the appropriate weights for the effects of precipitation amounts in each month upon growth and to calculate weighted means for the precipitation of each year.

Eigenvectors of tree growth derived for the longer subperiod 1700–1930 provide a basis for evaluating the stability of tree-growth and precipitation anomaly patterns during the past few decades. The four most important tree-growth anomaly patterns for 1700–1930 (figs. 1 and 2, maps 9, 10, 11, and 12) account for 45 percent of the total variance in this subperiod (table 1). They appear similar to those for 1931–1962, and they occur in the same relative order of importance. When the four most important anomaly patterns derived for 1700–1930 are extended into the independent subperiod (1931–1962), they account for 36.3 percent of the variance. In contrast, only 29.9 percent of the total variance is explained when the 1931–1962 eigenvectors are extended in to the earlier and longer subperiod.

Although the first three eigenvectors of tree growth for the subperiod 1700–1930 account for less variance in the dependent subperiod, the correlations between observed and estimated amplitudes (table 3) show that they are good predictors of the amplitudes of the first three eigenvectors derived for the subperiod 1931–1962. Similarly, the first three eigenvectors for 1931–1962 are good predictors of the amplitudes of the corresponding eigenvectors

TABLE 3.—*Correlation between two sets of amplitudes of tree-growth eigenvectors 1700–1930 and 1931–1962. The amplitude series for the first four eigenvectors in each subperiod were extended using independent data from the alternate subperiod. Correlation coefficients were then calculated for the amplitude series of eigenvectors of comparable rank*

Correlation period	Eigenvector	Characteristic pattern	Correlation coefficient
1931–1962	1	A	0.991
	2	B	.951
	3	C	.895
	4	D	−.082
1700–1930	1	A	.984
	2	B	.956
	3	C	.825
	4	D	−.057

derived for the 1700–1930 subperiod. However, in each case, the fourth eigenvector (pattern D) is a poor predictor of the fourth amplitude in the alternate subperiod. Study of the correlation coefficients obtained from comparison of amplitude series for the fourth eigenvector in each subperiod with the amplitudes of higher order eigenvectors in the alternate subperiod showed that, in each case, the fourth eigenvector was most similar to the sixth and seventh eigenvectors of the other subperiod.

4. DISCUSSION AND CONCLUSIONS

Characteristic anomaly patterns delineated by principal component analysis of monthly precipitation amounts over the Western United States, 1931–1966, seem to be reflected in corresponding patterns of tree growth. The first three characteristic patterns obtained from analysis of tree-ring data for 1931–1962 are similar to those obtained from data for 1700–1930. The precipitation anomaly patterns that have dominated during the past three decades seem to have persisted for at least 260 yr and are thus likely to maintain their importance during at least the immediate future. However, a fourth anomaly pattern recognizable in both the tree-ring and precipitation data since at least 1931 is different from an earlier pattern of comparable rank and is thus unlikely to maintain its recent importance.

Sellers (1968*b*) suggests that the characteristic patterns in precipitation correspond with anomalies in the circulation pattern aloft. Investigations now in progress show that relationships exist between tree-growth amplitudes and surface-pressure anomalies over the western half of the Northern Hemisphere and that there is significant agreement with pressures at certain latitudes and longitudes (Fritts 1970).

Other studies of tree-growth anomaly patterns that are underway include comparisons with precipitation and temperature anomalies that have occurred throughout the entire year (14 mo starting in June and ending with July). The agreement between anomalous patterns of tree growth and patterns in a variety of climatic data point to the potential value of eigenvector amplitudes derived from long time series of tree-ring data. These series greatly exceed the length of existing climatic data and therefore can be examined for differences in means and variances and for periodicities, trends, persistence, or other features lending possible forecasting value. Also, these tree-growth anomaly patterns can be calibrated with the existing climatic data, and the significant relationships can be used to reconstruct anomalous patterns that have probably occurred in the climate of the past.

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